

UHE neutrinos: higher twists, scales, saturation¹

R. Fiore¹ and V.R. Zoller²

¹*Dipartimento di Fisica, Università della Calabria
and*

*Istituto Nazionale di Fisica Nucleare, Gruppo collegato di Cosenza,
I-87036 Rende, Cosenza, Italy*

²*ITEP, Moscow 117218, Russia*

Abstract. It is shown that in the ultra-high energy neutrino interactions the higher twist corrections brought about by the non-conservation of the top-bottom current dramatically change the longitudinal structure function, F_L . To the Double Leading Log Approximation simple and numerically accurate formulas for F_L and $\sigma^{\nu N}$ are derived.

1 What is UHE ?

Neutrinos coming from active galactic nuclei, gamma ray bursts [1] and emerging in more speculative scenarios like breakdown of Lorentz invariance and decays of super-massive particles have rather hard spectrum extending beyond $E_\nu \sim 10^{11}$ GeV [2]. These Ultra-High Energy (UHE) neutrinos probe the gluon density in the target nucleon at very small values of Bjorken x thus providing an opportunity of doing small- x physics in a new kinematical domain. The properties of the neutrino-nucleon total cross section $\sigma^{\nu N}(E_\nu)$ at E_ν above 10^8 GeV were analyzed by many [3].

2 Scales - prodotti tipici

The overall hardness scale of the process $\nu N \rightarrow \mu X$ is usually estimated as

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$$Q^2 \sim m_W^2. \quad (1)$$

Indeed, to the Double Leading Log Approximation (DLA)

$$\sigma^{\nu N} \propto \int dQ^2 \left(\frac{m_W^2}{m_W^2 + Q^2} \right)^2 \exp \sqrt{C \log(1/x) \log \log Q^2} \quad (2)$$

and the origin of Eq.(1) becomes evident. This observation entails (is based on) the smallness of the characteristic value of Bjorken x which is $x \sim m_W^2/2m_N E_\nu$.

3 When top enters the game

The above estimate, $Q^2 \sim m_W^2$, is not unreasonable only for light flavor currents. The top-bottom current needs special care. The phenomenon of Charged Current Non-Conservation (CCNC) pushes the hardness scale up to $\sim m_t^2$ [4].

4 F_L as a carrier of CCNC effects

Weak currents are not conserved. But in what way? For longitudinal/scalar W-boson the transition vertex $W_L \rightarrow t\bar{b}$ is $\propto \varepsilon_L^\mu J_\mu \propto \partial_\mu J_\mu \propto m_t \pm m_b$. Therefore, the observable quantity $F_L \propto \varepsilon_L^\mu T^{\mu\nu} \varepsilon_L^\nu$ called the longitudinal structure function provides a measure of the CCNC effect. Here $T^{\mu\nu}$ represents the imaginary part of the forward scattering Compton amplitude. The longitudinal component of the νN total cross section is proportional to F_L .

5 F_L and κ -factorization

The gauge invariant sum of diagrams like that shown in 1 results in

$$\frac{dF_L(x, Q^2)}{dz d^2\mathbf{k}} = \frac{Q^2}{4\pi^3} \int \frac{d^2\boldsymbol{\kappa}}{\boldsymbol{\kappa}^4} \alpha_S(q^2) \mathcal{F}(x, \boldsymbol{\kappa}^2) (V_S + A_S + V_P + A_P), \quad (3)$$

where \mathcal{F} is un-integrated gluon density, $\boldsymbol{\kappa}$ - gluon momentum, z, \mathbf{k} - Sudakov's variables of t-quark. We find it convenient to separate contributions of the light cone Fock states $|t\bar{b}\rangle$ with angular momentum $L = 0$ (S-wave) and $L = 1$ (P-wave). The appearance of the P-wave component is the manifestation of the CCNC.

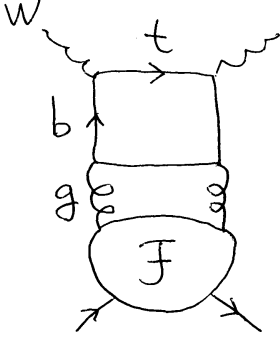


Figure 1: The forward Compton scattering amplitude

6 Higher twists. P-wave: $|W\rangle \rightarrow |t\bar{b}, L = 1\rangle$

Normally, the transition of the light cone scalar W -boson into the P-wave $q\bar{q}'$ -state is suppressed by the factor m_q^2/Q^2 [4]. However, in the case at issue $m_q^2 \equiv m_t^2 \gg Q^2 \sim m_W^2$ and, consequently, there is no suppression at all. Upon the azimuthal averaging

$$\langle V_P(m_t, m_b) \rangle \simeq \frac{(m_t - m_b)^2 \kappa^2 (\mathbf{k}^4 + \varepsilon^4)}{Q^2 (\mathbf{k}^2 + \varepsilon^2)^4} \quad (4)$$

and $\langle A_P(m_t, m_b) \rangle = (g_A/g_V)^2 V_P(m_t, -m_b)$, where $\varepsilon^2 = z(1-z)Q^2 + (1-z)m_t^2 + zm_b^2$.

In the soft gluon approximation, $\kappa^2 \ll k^2 + \varepsilon^2$, and the P-wave component of

$$F_L = F_L^S + F_L^P \quad (5)$$

is dominated by highly asymmetric configurations with [5]

$$z \sim 1 - \frac{m_b^2}{m_t^2 + Q^2}.$$

Therefore,

$$F_L^P(x, Q^2) \simeq \frac{m_t^2}{m_t^2 + Q^2} \int_{m_b^2}^{m_t^2} \frac{d\varepsilon^2}{\varepsilon^2} \frac{\alpha_S(\varepsilon^2)}{3\pi} G(x, \varepsilon^2) \quad (6)$$

Note, the factor $m_t^2/(m_t^2 + Q^2)$ emerges here as a property of the transition vertex $W \rightarrow t\bar{b}$ rather than the property of the interaction of the light cone $t\bar{b}$ -dipole with the target [5].

7 S-wave: $|W\rangle \rightarrow |t\bar{b}, L = 0\rangle$

Once again for soft gluons the azimuthal averaging leads to

$$\langle V_S(m_t, m_b) \rangle \simeq \frac{1}{Q^2} \left\{ 2Q^2 z(1-z) + (m_t - m_b) [(1-z)m_t - zm_b] \right\}^2 \frac{2\kappa^2 \mathbf{k}^2}{(\mathbf{k}^2 + \varepsilon^2)^4} \quad (7)$$

and $\langle A_S(m_t, m_b) \rangle = (g_A/g_V)^2 V_S(m_t, -m_b)$. The S-wave term in (5) integrated over \mathbf{k} has approximately uniform z -distribution. Then the DLLA estimate is as follows

$$F_L^S(x, Q^2) \simeq \frac{2\alpha_S(\overline{\varepsilon^2})}{3\pi} G(x, \overline{\varepsilon^2}), \quad (8)$$

where $\overline{\varepsilon^2} \simeq (Q^2 + 2m_t^2)/4$.

8 Numerical estimates

To DLLA the CCNC contribution to $\sigma^{\nu N}$ with the gluon density $G(x, k^2)$ from [6] is estimated as $\sigma_{CCNC}^{\nu N} \simeq 0.43 \times 10^{-31} \text{ cm}^2$ for $E_\nu = 10^{12} \text{ GeV}$. We neglected here the contribution of hard gluons to the proton longitudinal structure function. Therefore, the DLLA gives the lower estimate for F_L .

For comparison, the frequently used massless approximation gives at $E_\nu = 10^{12} \text{ GeV}$ the cross section $\sigma^{\nu N}$ that for different gluon densities varies in the range [7]

$$0.2 \times 10^{-31} \text{ cm}^2 < \sigma^{\nu N} < 1.5 \times 10^{-31} \text{ cm}^2$$

9 Scales and saturation

At small- x the unitarity/saturation effect enters the game [8, 9]. In massless approximation the unitarity correction to $\sigma^{\nu N}$ was found to be a 50 per cent effect [10]. In particular, it was shown that the unitarity effect turns $\sigma_{CC}^{\nu N} \simeq 1. \times 10^{-31} \text{ cm}^2$ at $E_\nu = 10^{12} \text{ GeV}$ into $\sigma_{CC}^{\nu N} \simeq 0.5 \times 10^{-31} \text{ cm}^2$. The strength of the unitarity/saturation effect depends on the hardness scale of the process, the first higher twist correction is estimated as [11]

$$\sim \frac{\alpha_S(Q^2)}{Q^2} \frac{G(x, Q^2)}{\pi R^2}$$

The CCNC hardness scale, m_t^2 , is much “harder” than the hardness scale for the light flavor currents. The latter is $\lesssim m_W^2$. Thus we conclude that the unitarity affects strongly the light quark contribution to $\sigma^{\nu N}$ but leaves the CCNC term intact.

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References

- [1] J. K. Becker, *Physics Reports* **458**, 173–246 (2008).
- [2] M. Drees, *Pranama - J. Phys* **62**, 207–218 (2004).
- [3] M. Glück, P. Jimenez-Delgado, and E. Reya, *Phys. Rev.* **D81**, 097501 (2010); Yu Seon Jeong, and Mary Hall Reno, *Phys. Rev.* **D81**, 114012 (2010); N. Armesto, C. Merino, G. Parente, and E. Zas, *Phys. Rev.* **D77**, 013001 (2008); R. Fiore, L. L. Jenkovszky, A. V. Kotikov, F. Paccanoni, A. Papa *Phys. Rev.* **D73**, 053012 (2006); R. Fiore, L. L. Jenkovszky, A. V. Kotikov, F. Paccanoni, A. Papa, and E. Predazzi, *Phys. Rev.* **D71**, 033002 (2005); *Phys. Rev.* **D68**, 093010, (2003); M. V. T. Machado, *Phys. Rev.* **D70**, 053008 (2004); J. Kwiecinski, Alan D. Martin, and A. M. Stasto, *Phys. Rev.* **D59**, 093002 (1999).
- [4] R. Fiore, and V. R. Zoller, *Phys. Lett.* **B681**, 32–36 (2009).
- [5] R. Fiore, and V. R. Zoller, *JETP. Lett.* **87**, 524-530, (2008).
- [6] I. P. Ivanov, and N. N. Nikolaev, *Phys. Rev.* **D65**, 054004 (2003).
- [7] E. M. Henley, and J. Jalilian-Marian, *Phys. Rev.* **D73**, 094004 (2006).
- [8] O. V. Kancheli, *Sov. Phys. JETP Lett.* **18**, 274–277 (1973).
- [9] N. N. Nikolaev and V. I. Zakharov, *Phys. Lett.* **B55**, 397–399 (1975); V. I. Zakharov and N. N. Nikolaev, *Sov. J. Nucl. Phys.* **21**, 227–228 (1975).
- [10] K. Kutak and J. Kwiecinski, *Eur. Phys. J.* **C29**, 521–530 (2003).
- [11] L. V. Gribov, E. M. Levin, and M. G. Ryskin, *Phys. Rep.* **100**, 1-150 (1983); A. H. Mueller and J. Qiu, *Nucl. Phys.* **B268**, 427–452 (1986).